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THE DESIGN OF THE OPTIMUM HULL FOR A LARGE LONG-RANGE FLYING BOAT

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SUMMARY

Principles for designing the optimum hull for a large long-range flying boat are proposed to suit the requirements of minimum drag, seaworthiness, and ability to take off and land at all operational gross weights. The principles include the use of moderate gross-load coefficients, ample forebody lengths, and deep steps and the close adherence of the form to that of a streamline body of revolution with a moderate fineness ratio.

The validity of the design principles is illustrated by the results of tests in NACA tank No. 1 and in the NACA two-dimensional low-turbulence pressure tunnel of the form of the hull for a 400,000-pound transport flying boat. These results indicate that for large airplanes satisfactory hydrodynamic characteristics can be attained without an undue penalty in flight performance caused by the drag of the step and the chines.

The effect of size on the proportions and the take-off performance of long-range flying boats is shown for three hypothetical flying boats having gross weights of 120,000, 300,000, and 480,000 pounds and the same wing loading, power loading, and hull loading. When these loadings are held constant, the size of the hull relative to the wing and the take-off time and distance are decreased as the gross weight is increased.

The hull of the flying boat, aside from its inherent ability to take off and land at sea, provides an immediate solution for the landing-gear problem of large long-range airplanes.

INTRODUCTION

The optimum hull for a long-range flying boat is one that performs the functions of a fuselage, flotation gear, and landing gear with the minimum of weight and drag. The ideal hull would be a streamline body of revolution with its maximum radius determined by the space for useful load and its fineness ratio determined by the length from the center of gravity to the tail surfaces.

Practicable hulls depart from the ideal in order to meet the following additional requirements that must be approximately satisfied if the flying boat is to be a self-sufficient and reliable unit of transportation:

(1) Seaworthiness in sheltered waters and moderate open-sea conditions. By seaworthiness is meant the ability to operate successfully as a surface boat without undue damage or danger from wind, waves, and spray.

(2) Ability to take off and land on the water at all operational gross weights. This requirement includes (a) water resistance low enough for reasonable take-off time and distance and (b) adequate hydrodynamic stability and control in pitch, yaw, and roll.

The best all-round compromise among aerodynamic, hydrodynamic, and structural requirements devised so far is the widely used V-bottom planing-type hull consisting of a forebody planing surface with the angle of dead rise increased at the bow to give sharp water lines, a step slightly aft of the center of gravity, and a pointed afterbody planing surface set at an upward angle with reference to the forebody. Such a hull blends with the airplane design in much the same way as a landplane fuselage except that a high location of the wing and a single vertical tail are desirable for clearance from spray. The V-bottom permits a reasonable weight of structure. The hull trims naturally at low water speeds for acceptable maximum (hump) resistance with the power loadings normally required in flight and for the minimum spray from the forebody. At planing speeds it is controllable in trim and can be pulled up for take-off. Its stability is such that it can be maneuvered and operated by the usual flight controls.

The adaptation of the type of hull described to various seaplane designs and research on its proportions and shape have been the principal activities of the seaplane towing tanks. The results of this work, together with extensive full-scale experience, enable the design of a large long-range seaplane to be approached with reasonable assurance that the design of a satisfactory hull can be accomplished with a reasonable amount of tank testing in addition to the usual wind-tunnel testing.

In this report, certain principles for the design of hulls for large long-range flying boats based on the accumulated experience of the NACA tanks are proposed. Their validity as applied to large airplanes is established by the results of an investigation of the hull of a 400,000-pound cargo flying boat, incorporating the principles and tested at the NACA laboratory at Langley Field, Va. Preliminary designs of three similar flying boats with the same form of hull are presented to illustrate the possibilities of water-based airplanes in the range of gross weights from 100,000 to 500,000 pounds and to indicate the effect of gross weight in this range on the relative size of hull to wing and on take-off performance.

DESIGN PRINCIPLES

The final form of a flying-boat hull is obtained from a succession of three-view outline drawings of the airplane, in which proportions and shape are adjusted until all the requirements are met in as satisfactory a manner as possible. This process entails a number of compromises and demands on the part of the designer, familiarity with all the aerodynamic, structural, and hydrodynamic principles involved, plus a sixth sense of what looks right. The detail design of the hull cannot be undertaken until the three views demonstrate that its shape and proportions blend harmoniously with the other components and the over-all design of the airplane.

Proportions

Aside from the fundamental requirements of cubic capacity and minimum drag, the proportions of the hull are largely dependent on the maximum gross weight, which determines the buoyancy and size of the planing surfaces required. A sound and not over-optimistic estimate of the gross weight is the most important contribution to a successful hull design. An overloaded hull will surely have inferior seaworthiness and hydrodynamic characteristics that will limit the pay load carried in everyday service or will result in excessive maintenance and repair. It is well to recognize this principle at the start by basing the hull proportions on a weight in excess of the first assumption in order to allow for the inevitable increases during the progress of the detail design.

Beam.- The beam may be selected by use of the expression

$$C_{\Delta_o} = \frac{\Delta_o}{wb^3} \qquad (1)$$

where

C_{Δ_o} gross-load coefficient

Δ_o gross load, pounds

w specific weight of sea water (64 lb/cu ft)

b maximum beam over chines, feet

Values of C_{Δ_o} vary widely in practice. Earlier flying boats averaged about 0.35 but there has been a continual trend toward higher beam loadings in an attempt to reduce frontal area. Present-day Naval patrol bombers average about 0.9 to 1.0, which perhaps is too high for general-purpose cargo or passenger airplanes. Extensive experience with tank models and available information on full-size operation indicate that best over-all results are obtained with more moderate values of C_{Δ_o} ranging from 0.5 to 0.8, depending on the degree of conservatism desired.

As far as low-speed spray and general seaworthiness are concerned, the permissible values of C_{Δ_o} are associated with length-beam ratio because the detrimental effects of a small beam can be to some extent compensated for by increasing the length. How far this principle can be carried is a subject for further research and, in the meantime, satisfactory results are more certain with the more moderate beam loadings. The acceptance of this principle will avoid some of the practical difficulties encountered with heavily loaded hulls and the extensive towing-basin tests required to make them tolerable for a new design.

Length.- The over-all length is made up approximately of the length of forebody plus the required distance from the center of gravity to the tail surfaces. The length of forebody is based on the seaworthiness required for the intended service.

It is shown in reference 1 that the length-beam ratios of the forebody for various flying boats in service are related by the expression

$$C_{\Delta_o} = k\left(\frac{L_f}{b}\right)^2 \tag{2}$$

where L_f is the length in feet of the forebody from bow to step and k is a coefficient ranging from 0.0525 for boats with very light spray to 0.0975 for boats with excessive spray. Satisfactory seaworthiness and low-speed spray characteristics may be obtained for flying boats with the values of C_{Δ_o} proposed previously and a design value of k of 0.0675 or less.

The optimum length of the afterbody from step to sternpost is also a subject for further research, particularly in regard to dynamic stability and landing characteristics. It is influenced primarily, however, by the buoyancy required aft of the center of gravity for acceptable trims at rest and the dynamic lift required at the hump speed for acceptable hump trims and hump resistance. Above the hump speed, the afterbody serves no useful purpose with regard to stability or resistance except as a fairing for the forebody in flight. For hulls with normal proportions, afterbody lengths from 2.3 to 2.7 beams have proved satisfactory and an average value of 2.5 may be assumed in advance of towing-basin tests of the specific design.

Depth.- The depth of the hull is as important a dimension as the beam, as far as frontal area, surface area, and drag are concerned. When the wing root is in the hull, as is usually the case, the depth of hull is greater than that of the equivalent fuselage for a landplane in order to provide spray clearance for the propellers and aerodynamic surfaces. The increment in depth required may be kept to a minimum by the use of moderate hull loadings because the height of the spray is a function of the bottom pressures. The spray normally strikes the flaps and horizontal tail, however, at speeds at which the bow is out of the water and the length of forebody has relatively little influence on the spray; hence this spray is a function of beam loading alone rather than the length-beam ratio.

There is no particular advantage in the use of very narrow beams to reduce frontal area if the hull must be made correspondingly deeper to obtain spray clearances. The optimum ratio of beam to height has not been determined. The best rule is to adhere to the moderate hull loadings proposed and make the depth compatible with the general design.

Depth of step.- It is a natural tendency to use as small a depth of step as possible in order to keep the discontinuity in form and structure as well as the hump resistance at a minimum. If the step is too shallow, however, the water resistance at high speeds is inordinately high and the hull becomes violently unstable near the take-off and landing speeds. The instability results in jump take-offs and skipping below flying speed, which are extremely hazardous and may even be catastrophic. The choice of the depth of step therefore demands the utmost consideration.

The minimum depth of step to avoid the hydrodynamic instability may be determined experimentally by tank tests of a dynamically similar model of the airplane. It is shown in reference 2 that, with wing loadings of from 35 to 45 pounds per square foot, depths of 5 percent of the beam are inadequate for stable high-attitude landings. The acceptance, at the beginning of the designs, of a depth at the keel from 8 to 12 percent of the beam will avoid most of the operational difficulties associated with hydrodynamic instability at high water speeds.

Angle between forebody and afterbody keels.- The relatively large angle between the keels forward and aft of the step constitutes a conspicuous difference between planing boats and seaplane hulls. Its principal purpose on the seaplane hull is to provide clearance at high water speeds in order that the airplane may take off and land at high lift coefficients. If the angle between the keels is too low, the trim at low speeds before the hump speed is too low and the resistance is higher than at the true hump, whereas the resistance at high planing speeds is too high because of the frictional resistance of the wetted afterbody. If the angle of afterbody keel is too high, the trims at rest and at the hump speed are unduly high. The best compromise appears to be 6° or 7°.

Relative location of wing and hull.- The best fore-and-aft location of the wing with respect to the step of the hull is that where the stable range of positions of the center of gravity for flight corresponds as far as possible to the stable range for take-offs and landings. The location of the hydrodynamic stable range depends on the relative position of center of gravity and step. The determination of this range is one of the main purposes of tank tests of a dynamic model of a proposed design. In the model tests, all the important trimming moments, including those due to thrust and slipstream, must be simulated in order to predict accurately the stable positions of the center of gravity of the full-size airplane. If the hydrodynamic stable range is too far aft with respect to the aerodynamic range, the hull may be moved forward or, as is more convenient in later stages of the design, the step alone may be moved forward, and vice versa. When the location of the step itself is changed, care must be taken to maintain the proper depth of step by vertical displacement of the forebody or afterbody.

In advance of the specific model tests, the step may be approximately located on a line that extends vertically through the estimated mean position of the center of gravity when the airplane is in the stall attitude. In the case of a step having a plan form other than transverse, its effective longitudinal position may be taken as that of the centroid or center of gravity of the plan-form area of the step (reference 3).

Shape

When the over-all proportions and the dimensions of the planing surfaces are decided upon, the minimum drag may be obtained if the lines of the hull conform with the following general principles that are self-evident but are sometimes overlooked in practice:

(1) The departures from a streamline body should be kept at the minimum consistent with the desired hydrodynamic characteristics

(2) Although the actual cross sections must depart from the ideal, the curve of section areas should follow that of the streamline body as closely as possible

(3) The chines should be disposed along the probable flow lines around the body as far as possible, particularly at the bow

(4) The actual shape of the hull at every point should be smooth and fair in three dimensions except for the necessary discontinuities at the chines and step

For gross-load coefficients less than 0.3, a streamline body of revolution with a moderate fineness ratio may be readily adapted as the basic form to follow for the hull lines. The probable flow lines about such a body are roughly apparent and will not be influenced greatly by the addition of the V-bottom planing surfaces. The elevated position of the stern, which is desirable for practicable hulls, may be obtained with the minimum of penalty in drag by smoothly warping the axis of revolution. When the height of hull is greatly different from the breadth, an elliptical cross section provides the closest approximation to the circular section of the body of revolution.

The curve of section areas provides an additional guide for the proper fairing of the lines. The fairing for a shape as complex as a flying-boat hull is best accomplished by the methods used by naval architects in obtaining the smooth and pleasing contours of the form of a ship. The desired form should be so well defined by offsets and measurements that little freedom remains in the full-size lofting of the lines.

Below the chines, the shape must conform to that found by experience to have suitable hydrodynamic characteristics but otherwise should be smooth and fair for the minimum of interference to the flow of water or air and for ease of construction. Angles of dead rise, exclusive of chine flare, of approximately 20° to 22.5° have been found to be generally acceptable in full-size operation for normal take-offs and landings.

A fundamental principle in the fairing of the forebody bottom apparently is to maintain a cylindrical form of the forebody planing surface as far forward of the step as proper fairing of the lines at the bow will allow. A rough rule is that the buttocks should be straight and parallel for at least 1.5 beams forward of the step in order to obtain satisfactory spray, resistance, and stability characteristics. If the buttocks remain straight too far forward, however, they will become too convex at the bow and the cleanness of running at taxying speeds will be impaired. Part of the improvement in spray characteristics that results from lengthening the forebody can usually be attributed to the finer water lines and improved fairing made feasible by the greater length.

A detailed exposition of the shape below the chines is beyond the scope of this report. Information regarding most of the important parameters of form may be found in the various reports of fundamental researches in the NACA tanks. (See bibliography.)

The form below the chines finally adopted should always be investigated in the towing tank before the structural design of the hull is begun. During the tank tests, small modifications in shape are sometimes found that offer the possibility of large improvement in the hydrodynamic characteristics but, if the design is too far advanced, these modifications are difficult to incorporate in the full-size hull.

TYPICAL APPLICATION OF DESIGN PRINCIPLES AND RESULTS

There is no optimum form of hull for all flying boats just as there is no optimum form of fuselage, wing section, or propeller for all airplanes. The hull in every case must be tailored to fit the design by use of the broad principles outlined and by the results of wind-tunnel and tank tests of the most promising preliminary form. Adoption of the more conservative principles at the inception, however, will result in a large reduction in the experimental work.

NACA Model 84-FF

NACA model 84-FF is one of an extensive series of hulls designed and investigated by the NACA for the purpose of developing forms that would combine low air drag with good hydrodynamic qualities. This investigation is described in reference 4. The lines and proportions of model 84-FF are shown in figure 1. They are based on a streamline body of revolution having the maximum radius at 30 percent of the length and a fineness ratio of 7.22. Clearance at the bow and stern are obtained by warping upward the axis of revolution forward and aft of the maximum radius. The lines of the forebody are exterior to the basic form and are such that the height is 6 percent greater than the beam. The depth of step and length of afterbody, however, are small as compared with those in current use, and the length from step to tail is too short for present-day airplanes.

According to equation (2), a value of k of 0.0675 gives a maximum practical value of C_{Δ_o} (equation (1)) of 0.67 for the length-beam ratio of the forebody used. The results of the tank tests reported in reference 4 indicate that the resistance and spray characteristics at this gross-load coefficient are satisfactory. In the light of more recent experience, however, the depth of step and length of afterbody are questionable with respect to the buoyancy needed aft and to the hydrodynamic stability.

Aerodynamic tests in the NACA 8-foot high-speed tunnel (reference 4) indicate that model 84-F (84-FF without the chine flare) has a minimum drag coefficient of 0.098 based on frontal area with transition fixed at 5 percent of the length at a Reynolds number of 20.5×10^6. This coefficient is only 18 percent greater than that of the streamline body of revolution from which the hull was derived and demonstrates the validity of the principles on which the form was based. The increase in drag caused by the chine flare was not determined in these tests but can be assumed to be small.

NACA Model 155

The form of the hull of the 400,000-pound cargo airplane (NACA model 155), adapted from that of model 84-FF, is shown in figure 2 and illustrates the deviations from the standard form thought necessary or desirable for this specific design. The maximum width was determined by the cargo requirements and is somewhat greater than the beam over the chines. The maximum gross-load coefficient is 0.65, which is based on a load well in excess of the normal gross weight that was assumed at the time of the preliminary design. This beam loading, together with an increased forebody length-beam ratio, gives a value of k of only 0.0552, which assures a reserve of seaworthiness compatible with the general conservatism of the design and the requirements of the intended service as a long-range cargo carrier.

The depth of step is 9 percent of the beam in accord with recent experience with skipping and the length of afterbody is increased for additional buoyancy aft of the center of gravity. The length of tail extension is such that the predetermined tail arm is attained and the form aft of the sternpost is carefully faired in an attempt to reduce the drag of the afterbody.

Preliminary tests of a $\frac{1}{40}$-size model in NACA tank No. 1 indicated that, when the afterbody was immersed at high water speeds, the flow did not clear the tail extension. A small chine flare similar to that of model 84-FF, however, proved to be all that was required to make the lines satisfactory in this respect,

Wind-tunnel tests.- Following the preliminary tank tests, the aerodynamic drag of the same model in combination with a proposed NACA low-drag wing was extensively investigated in the NACA two-dimensional low-turbulence pressure tunnel. The significant results of the wind-tunnel tests are shown in figure 3, in which

$$C_{D_A} = \frac{D_c - D_w}{qA}$$

where

C_{D_A} frontal-area drag coefficient

D_c drag of surveyed portion of wing-hull combination

D_w drag of surveyed portion of wing alone

A maximum cross-sectional area of hull

q dynamic pressure

The model was tested in the smooth condition and with transition fixed by artificial roughness at a point 5 percent of the length of the hull from the bow. As in the aerodynamic tests of reference 4, drag coefficients with fixed transition are considered more nearly representative of actual full-size values than the drag coefficients of the smooth model.

With fixed transition, the minimum drag coefficient of the hull is 0.0795 as compared with 0.0983 for model 84-F at approximately the same Reynolds number. In comparing these values, the differences in the test procedures and conditions should be considered as well as the differences in form.

For the smooth condition, the minimum drag coefficient is 87 percent of the minimum drag coefficient with transition fixed at 5 percent of the length. This result indicates that laminar flow can persist over a considerable portion of the forebody aft of the 5-percent point and that the chines at the bow are favorably disposed with respect to the flow.

A fairing aft of the very deep step, having a length 14 times the depth of step, reduces the minimum drag coefficient 13 percent in the smooth condition. If the same increment is applied to the minimum drag coefficient with fixed transition, shown by the short-dash curve of figure 3, the corresponding reduction is 11 percent. These percentages are indicative of the proportion of the total drag of the hull attributable to the deep step.

The merit of the form is best judged by comparing its drag with the drag of a flat plate having the same surface area. This comparison is made in figure 3 by including the numerical value of the coefficient of skin friction with fully turbulent boundary layer at the test Reynolds number multiplied by the ratio of the surface area of the model to its frontal area. The resulting coefficient is 70 percent of the minimum drag coefficient of the hull with fixed transition and is 79 percent of the estimated minimum drag coefficient with fixed transition and the step faired. The form drag of the hull, including the drag of the chines, may therefore be estimated to be of the order of only 21 percent of the total drag.

Tank tests.- Following the tests of the $\frac{1}{40}$- size model of the hull, the hydrodynamic characteristics of a $\frac{1}{16}$-size dynamic model of the airplane, equipped with scale powered propellers that developed 70 percent of the scale thrust, were investigated. These tests showed the design to have excellent take-off and landing stability, comparative freedom from porpoising at the desired positions of the center of gravity, and full clearance of propellers, flaps, and tail surfaces from objectionable spray during take-offs at the full-load gross weight. The only further modification found necessary was the usual adjustment of the location of the step to obtain freedom from porpoising at the forward positions of the center of gravity required by the cargo loading schedules.

The limits of stability for the final form are shown in figure 4. The power-off trim track with the center of gravity at 26 percent of the mean aerodynamic chord and neutral elevator is well clear of the lower trim limit. The porpoising at high trims and high speeds is very mild, as evidenced by the small spread between the two branches of the upper trim limit.

The stable range of positions of the center of gravity is defined conservatively by assuming the elevators neutral at the forward limits and 15° up at the after limits. During operation with positions of the center of gravity close to these limits or in the event of a power failure on take-off, serious porpoising may be averted by moving the elevator up when near the forward limits or down when near the after limits. The range shown in figure 4 is ample for the various cargo loadings assumed in the design.

The stable range of positions of the center of gravity, power on, at a gross-load coefficient of 0.65 is from 24 to 36 percent of the mean aerodynamic chord, and the center of the range for normal operation is at 30 percent of the mean aerodynamic chord. With the center of gravity at 30 percent of the mean aerodynamic chord, a line through the center of gravity and the step is inclined at an angle of 15.3° from a perpendicular to the base line as compared with an angle of trim for a full-stall landing of approximately 14°.

NACA Model 180

The lines of NACA model 180 (fig. 5) illustrate the use of an elliptical streamline body as the basic form for a hull and the essential differences in proportions among various applications of the same design principles. The design gross-load coefficient is 0.76 and the length of forebody to the centroid of the step is such as to give a value of the coefficient k of 0.0657.

The incorporation of the V-step in the lines is in accordance with results of reference 5 showing that the mean depth of such a step can be less than the equivalent transverse step for similar landing stability. It is not yet established that the drag due to the V-step is appreciably less but the inherently smaller frontal area is an indication of a slight over-all advantage over the transverse step.

THREE PRELIMINARY DESIGNS FOR LARGE TRANSPORT FLYING BOATS

The immediate possibilities and broad technical aspects of large airplanes for overseas air routes are illustrated by the preliminary designs of three flying boats having gross weights of 120,000, 300,000, and 480,000 pounds. These gross weights are chosen arbitrarily to provide the same power loading with the P. & W. R-2800 engine, the P. & W. R-4360, and an eventual more powerful version of the R-4360 in combinations of four, six, and eight, respectively. There are thus represented a four-engine airplane within the scope of present practice, a six-engine airplane that is the next logical development in multiengine transports, and an eight-engine airplane that will follow naturally if the intermediate size proves satisfactory in all respects. The three airplanes are appropriately designated by the names of three ocean birds, Shearwater, Gannet, and Albatross.

Three-View Drawings

In order to maintain comparable physical dimensions and performance for the three sizes, the wing loadings and hull loadings are made the same, along with the power loadings. The arbitrary values chosen for these loadings and the other design assumptions held constant for all the gross weights are given in table I. The resulting data and dimensions for the three airplanes are given in table II. The corresponding three-view drawings are shown in figures 6, 7, and 8 and a comparison of the plan views to the same scale is shown in figure 9. A perspective drawing of the intermediate size, illustrating the anticipated trend for six-engine transports, is given in figure 10.

The three-view drawings show how the low-drag hull fits in with the other components of the structure and also the influence of the design assumptions on the proportions. The proportions of wing, hull, and tail surfaces change with the size because the dimensions of the wing with constant wing loading vary as the square root of the ratio of the gross weights; whereas the hull dimensions with constant gross-load coefficient vary as the cube root of the ratio of the gross weights. Inasmuch as the tail moment arms vary with the dimensions of the hull, the tail areas become a larger percentage of the wing area as the gross weight is increased. The sizes of the hulls and tail surfaces - relative to the wing - that follow from these dimensional relations are compared in figure 11.

There are, of course, innumerable variations of loadings and dimensions possible for any of the airplanes, depending on factors not taken into account in the present analysis and on the individual preferences of the designer. It appears that, as the size is increased, the hull of a flying boat can become relatively smaller and retain ample proportions for seaworthiness. The drag therefore becomes of less and less consequence in relation to the drag of the wing.

The length of the tail extension can probably be changed somewhat to vary the actual tail area required without sensibly affecting the drag of the hull.

The absolute clearances of the wing and propellers above the load water line increase with the size of the airplanes. The clearance of the bottom of the wing in proportion to the hull dimensions is slightly less as the size increases; the clearance of the propeller tips in proportion to the propeller diameter becomes greater as the size and number of engines are increased.

Take-Off Performance

The power loading of the three designs, primarily determined by the engines available and the long-range performance required, is relatively high for take-off; therefore, the question remains as to whether the water resistance of the low-drag hulls will limit their function as a landing gear. The approximate take-off performance and trend with size may be calculated from the data for model 84-EF-3 (reference 4).

Procedure.- Take-off calculations were made by using the data of reference 4 and the assumed values of aerodynamic lift and drag coefficient plotted in figure 12. The thrust was estimated from the data of reference 6 and gear ratios for the four-blade propellers were assumed to give the same thrust per horsepower with the three sizes of propeller. The hulls were assumed to be free to trim up to a speed beyond the hump at which the trim dropped to 5°, the trim being held at this value for the remainder of the take-off. The take-off speed at 5° trim (9° angle of attack of the wing) is approximately 96 miles per hour.

Results.- The curves of the computed values of air drag, total resistance, and thrust, along with the graphical determination of the take-off time and distance, are shown in figures 13 to 15. The curves indicate that, for large low-drag flying boats such as those under consideration, the critical point in the take-off is at the hump speed rather than near take-off speed and that the assumed power plants are sufficient to provide reasonable take-off times and distances for such large airplanes. The pertinent hydrodynamic data at the hump speed from the calculations are

	Shearwater	Gannet	Albatross
Trim, degrees	10.7	10.3	10.1
Load on water, pounds	101,000	236,000	360,500
Ratio load on water to gross weight	0.842	0.786	0.752
Water resistance, pounds	23,000	52,400	79,000
Ratio load on water to water resistance	4.38	4.50	4.64

The total resistance shown is conservative, because the trims at the hump speed and at take-off are higher than best trim and the resistances are uncorrected for the decrease in the coefficient of skin friction with increase in Reynolds number (reference 7). The estimated times and distances become less as the size of the airplane is increased, an indication that there is no reason to expect an unforeseen take-off problem for the larger flying boats.

With constant wing and power loadings, the favorable effect of size on the take-off performance is mainly a Froude number effect; in other words, the larger hulls operate at relatively lower speeds with respect to their dimensions. This favorable effect is brought out clearly in figure 16, in which the forces involved are reduced to nondimensional form by dividing them by the gross weight. As the size is increased the hump speed becomes higher. As a result, the load on the water is lower, the load-resistance ratio is higher, and the acceleration through the critical region is greater. The larger airplanes also take off at lower Froude numbers, and their high-speed resistances are relatively lower because they do not reach the Froude number at which the frictional resistance of the afterbody becomes predominant.

CONCLUDING REMARKS

The results of the investigations described indicate the practicability of the present form of flying-boat hull up to a gross weight of 500,000 pounds and support the validity of the design principles proposed. As the gross weight is increased, the volume of the hull becomes relatively less, so that the benefits of moderate hull loadings can be attained without undue penalty in weight and drag. The increment in drag caused by an adequately deep step is smaller than is the probable increment caused by unavoidable roughness on the full-size airplane. Close adherence to the form of a streamline body and a favorable disposition of the chines with respect to the flow result in drag coefficients largely attributable to the skin friction. Radical departures from the form for minimum drag, or forms having excessive surface area, will not in general be desirable for high-performance airplanes regardless of their hydrodynamic advantages.

Landing gears for landplanes have become relatively heavier and ground pressures with conventional arrangements have become higher as the gross weight has increased. The gears for gross weights above 140,000 pounds have not yet made their appearance but will probably take the form of multiple wheels or caterpillar treads to reduce the concentration of stresses in the airplanes and runways. The hull of the flying boat, aside from its inherent ability to take off and land at sea, provides an immediate solution for the landing-gear problem of large long-range airplanes.

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TABLE I.- LOADINGS AND DESIGN ASSUMPTIONS HELD CONSTANT

FOR THE THREE PRELIMINARY DESIGNS

Power plants - radial air cooled:	
Power loading, take-off, lb/hp	16.67
Power loading, cruising, lb/hp	27.75
Fuel consumption, lb/hp-hr	0.45
Propellers - constant speed:	
Number of blades	Four
Tip speed, take-off, fps	1050
Wing - NACA low-drag section:	
Wing loading, full-load gross weight, lb/sq ft	42.0
Aspect ratio	8.95
Taper ratio	2.575:1
Horizontal tail - NACA low-drag section:	
Volume/(Wing area × M.A.C.)	0.500
Aspect ratio	3.9
Taper ratio	2.46:1
Center of pressure, percent root chord	25
Vertical tail - NACA low-drag section:	
Volume/(Wing area × Span)	0.033
Aspect ratio	1.48
Taper ratio	2.09:1
Center of pressure, percent root chord	25
Hull:	
Gross-load coefficient	0.704
Coefficient k	0.0598
Ratio of length to maximum beam	8.64
Ratio of depth to maximum beam	1.25
Ratio of cargo space to gross weight, cu ft/lb	0.0459
Center-of-gravity position:	
Mean position, percent M.A.C.	30
Forward of step, percent maximum beam	20.85
Above keel, percent maximum beam	83.33

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TABLE II.- DATA AND DIMENSIONS FOR THE

THREE PRELIMINARY DESIGNS

	Shearwater	Gannet	Albatross
Full-load gross weight, lb	120,000	300,000	480,000
Power plant:			
Number of engines	Four	Six	Eight
Horsepower, per engine	1800	3000	3600
Horsepower, take-off	7200	18,000	28,800
Horsepower, cruising, at altitude of 10,000 ft . . .	4320	10,800	17,300
Propellers:			
Diameter, ft	15.2	18.0	19.0
Activity factor per blade	67	123	115
Wing:			
Area, sq ft	2857	7143	11,430
Span, ft	160	253	320
M.A.C., ft	19.1	30.2	38.2
Hull:			
Length, ft	130.8	177.2	207.5
Maximum beam, ft	15.1	20.5	24.0
Beam over chines, ft	13.9	18.8	22.0
Depth, ft	18.9	25.6	30.0
Space for cargo, cu ft	5500	13,700	22,000
Center of gravity:			
Distance forward of step, ft .	3.15	4.27	5.00
Height above keel, ft	12.6	17.1	20.0
Tail surfaces:			
Vertical area, sq ft	200	600	1100
Horizontal area, sq ft	360	1100	2000
Tail moment arm, ft	76	98	109

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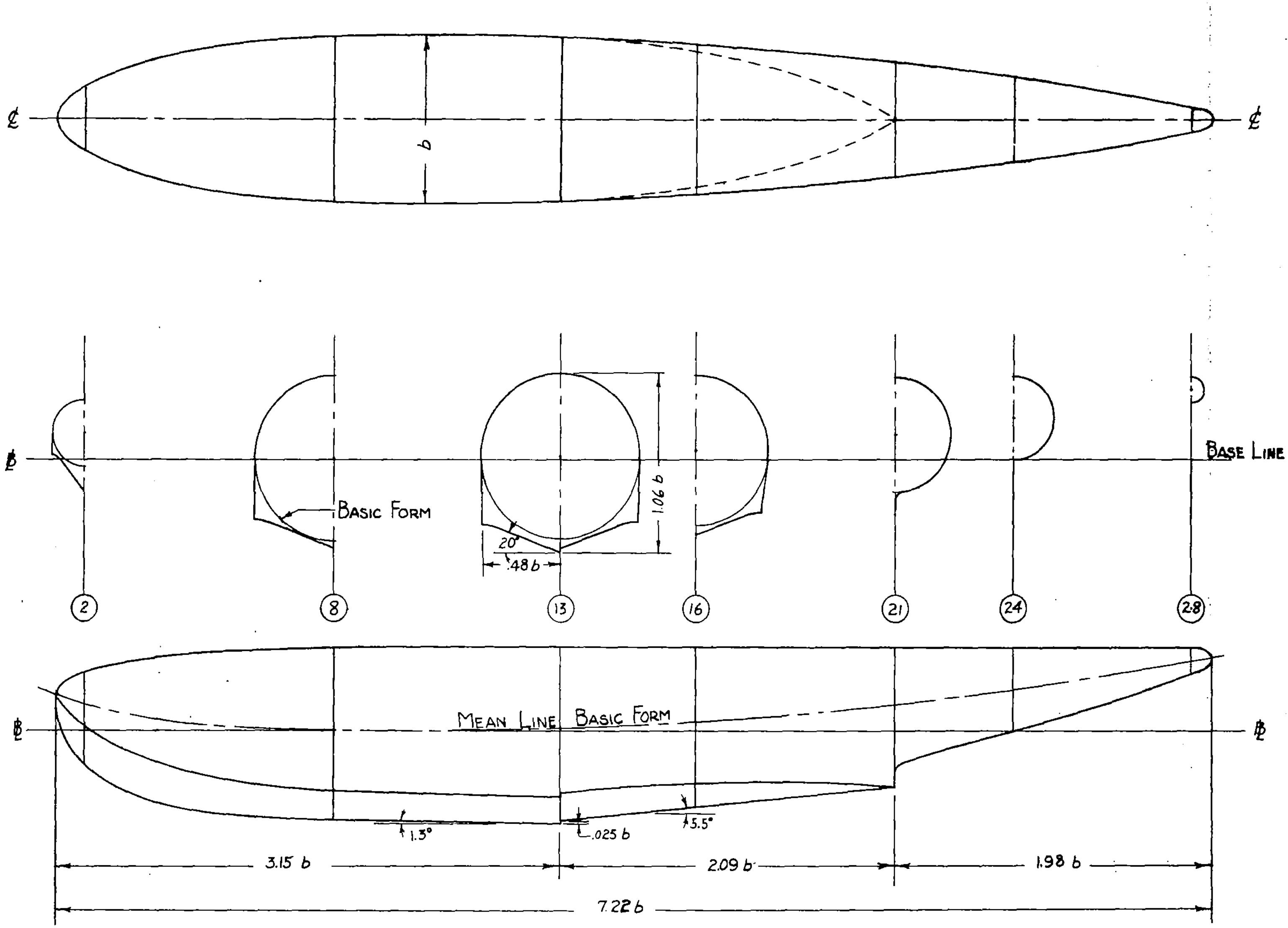

Figure 1.- Lines of NACA model 84-FF flying-boat hull.

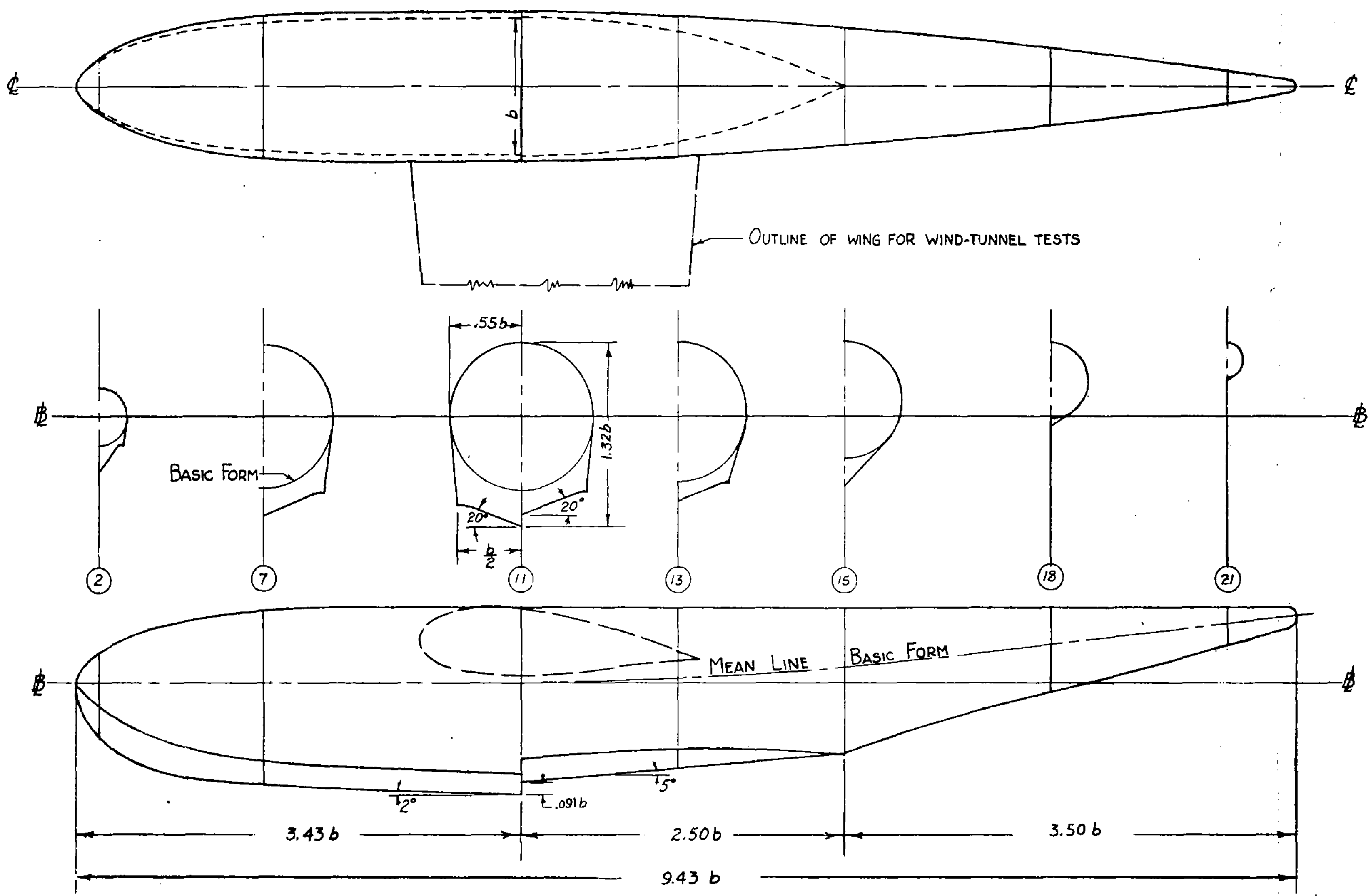

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Figure 2.- Lines of NACA model 155 flying-boat hull.

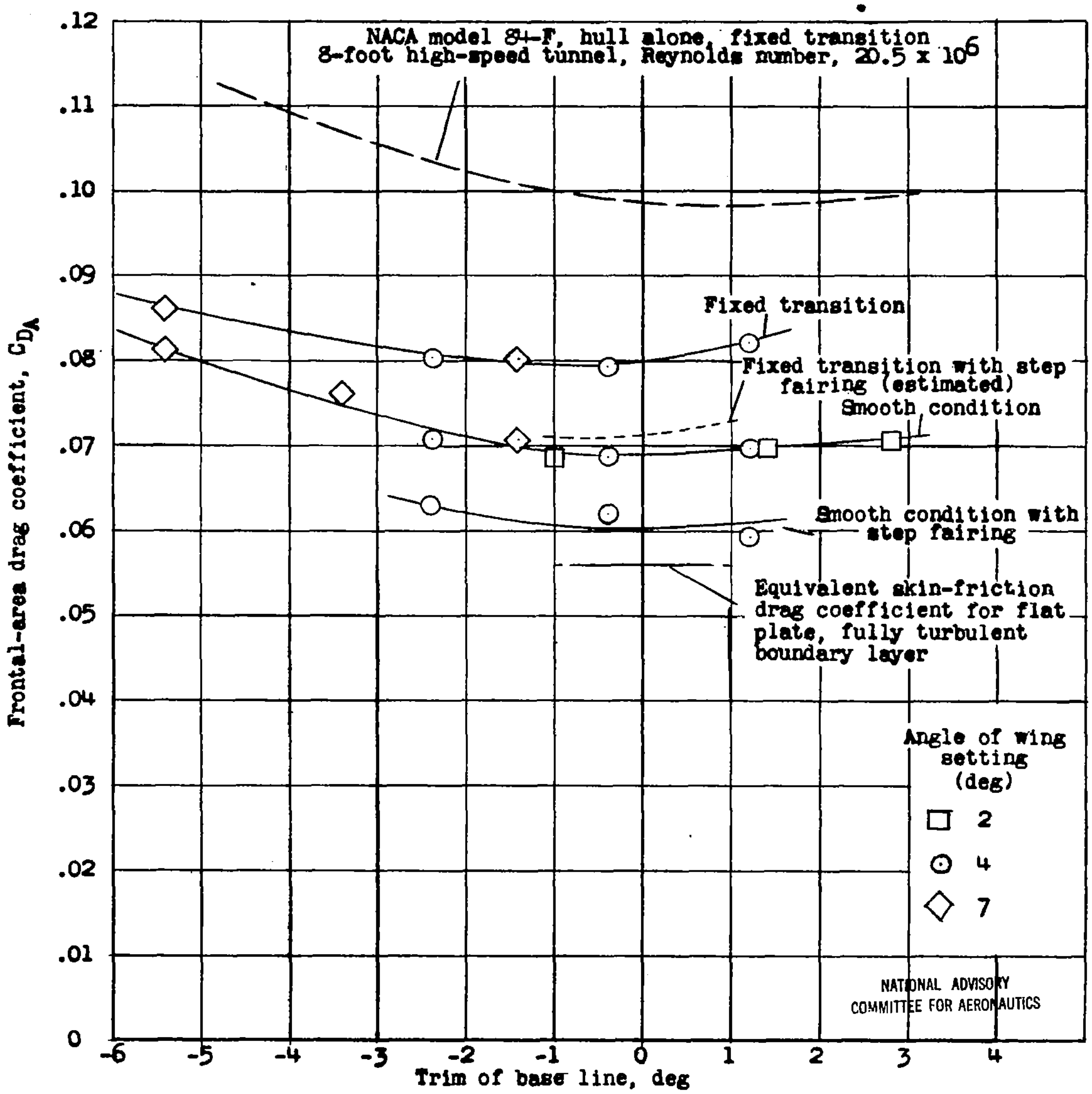
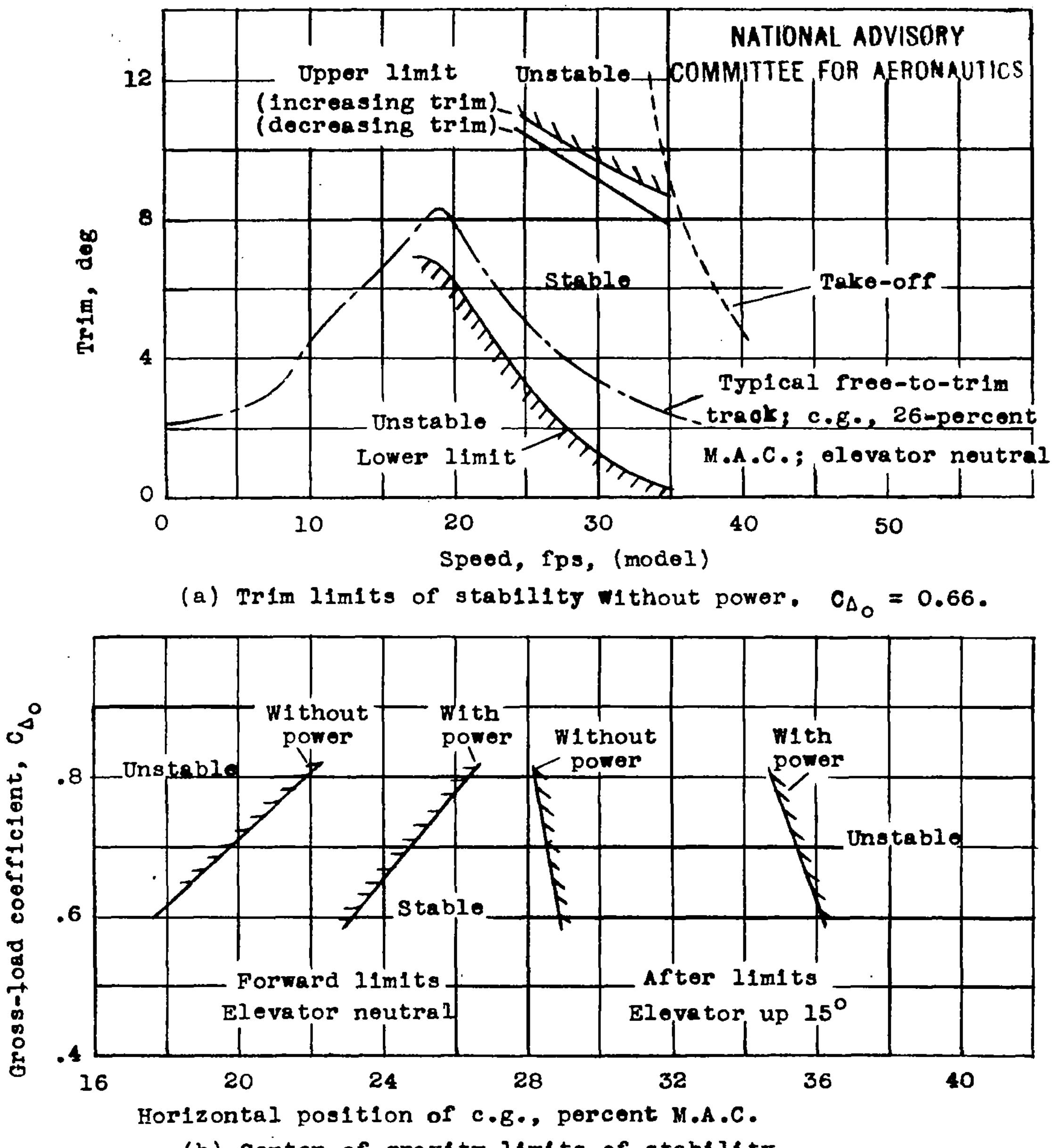


Figure 3.- Frontal-area drag coefficients of NACA model 155 flying-boat hull as determined in the NACA two-dimensional low-turbulence pressure tunnel. Reynolds number, 22.5×10^6.



(a) Trim limits of stability without power. $C_{\Delta_o} = 0.66$.

(b) Center-of-gravity limits of stability.

Figure 4.- Hydrodynamic stability characteristics of the 400,000-pound cargo airplane as determined from tests in NACA tank No. 1 of 1/16-size powered dynamic model. Flaps deflected 20°.

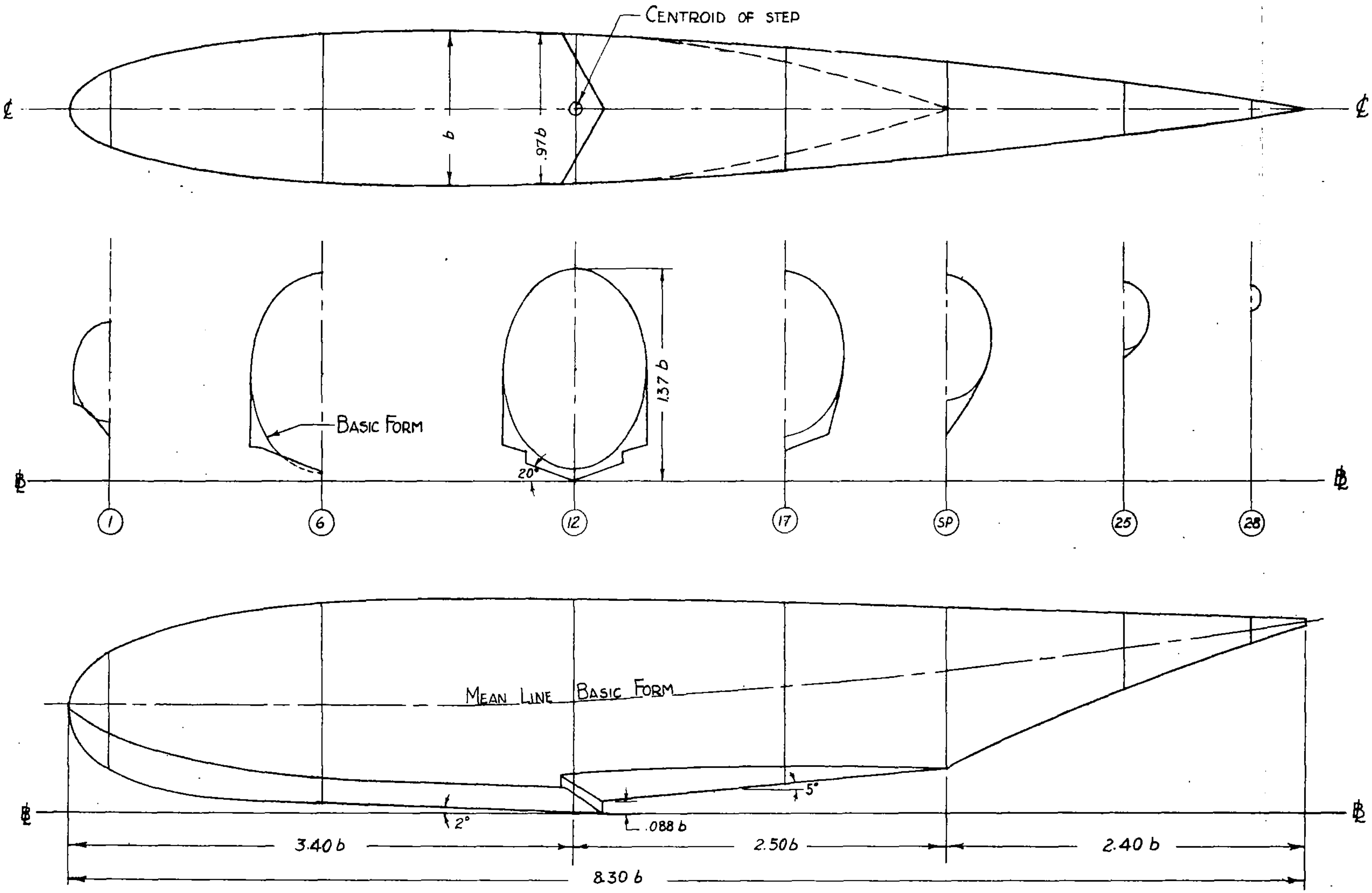


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Figure 5.- Lines of NACA model 180.

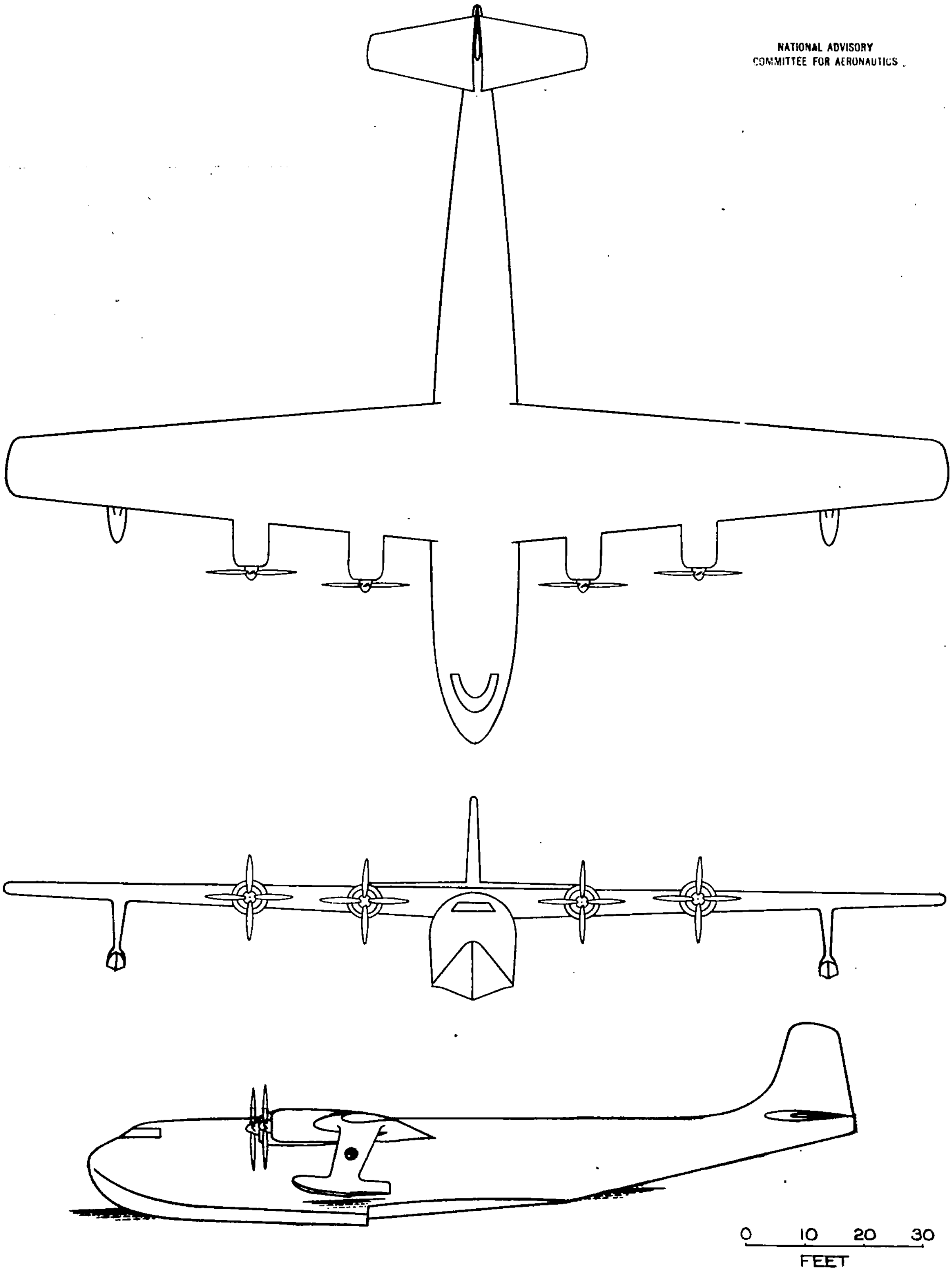

Figure 6.- Three-view drawing of Shearwater. Gross weight, 120,000 pounds.

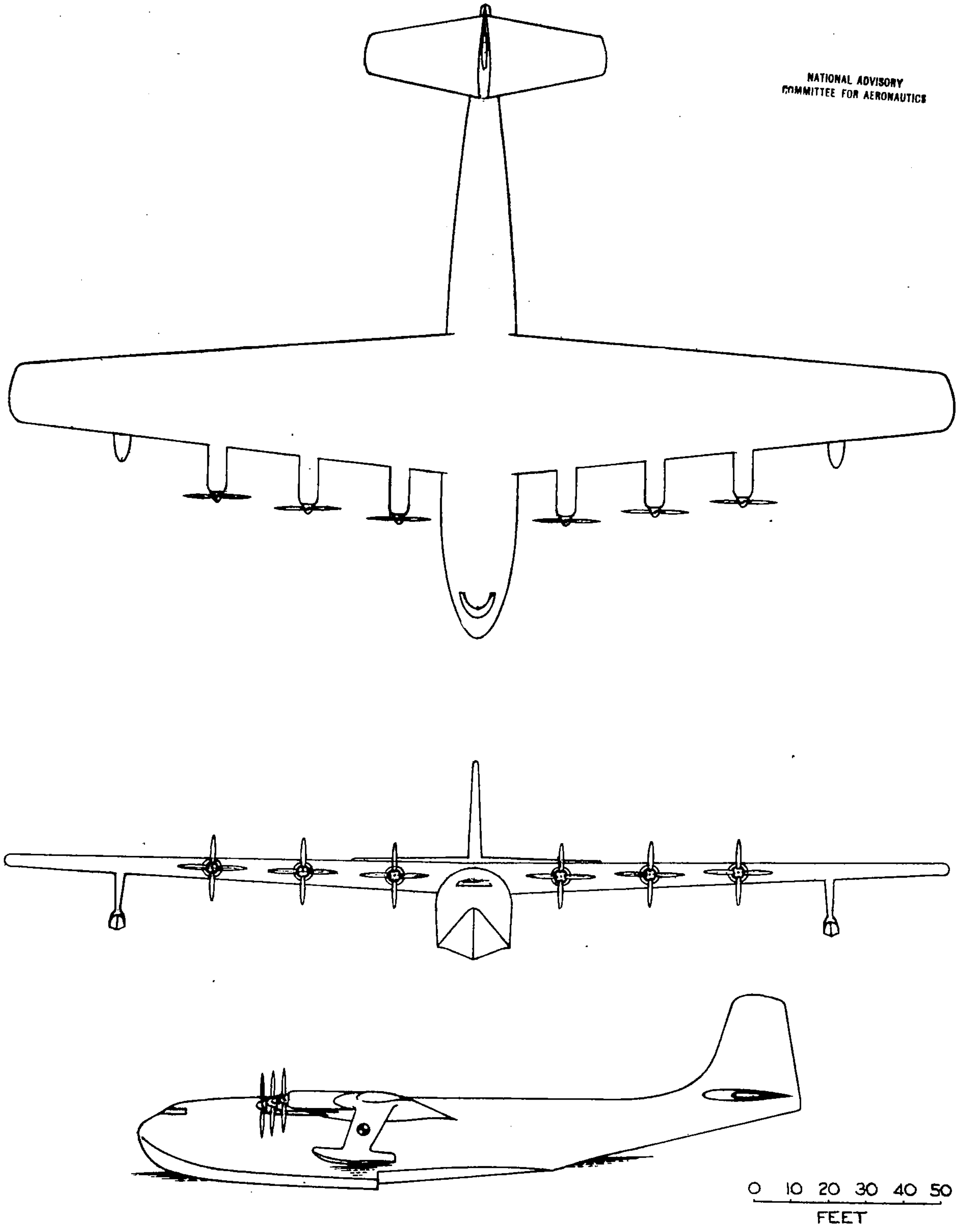

Figure 7.- Three-view drawing of Gannet. Gross weight, 300,000 pounds.

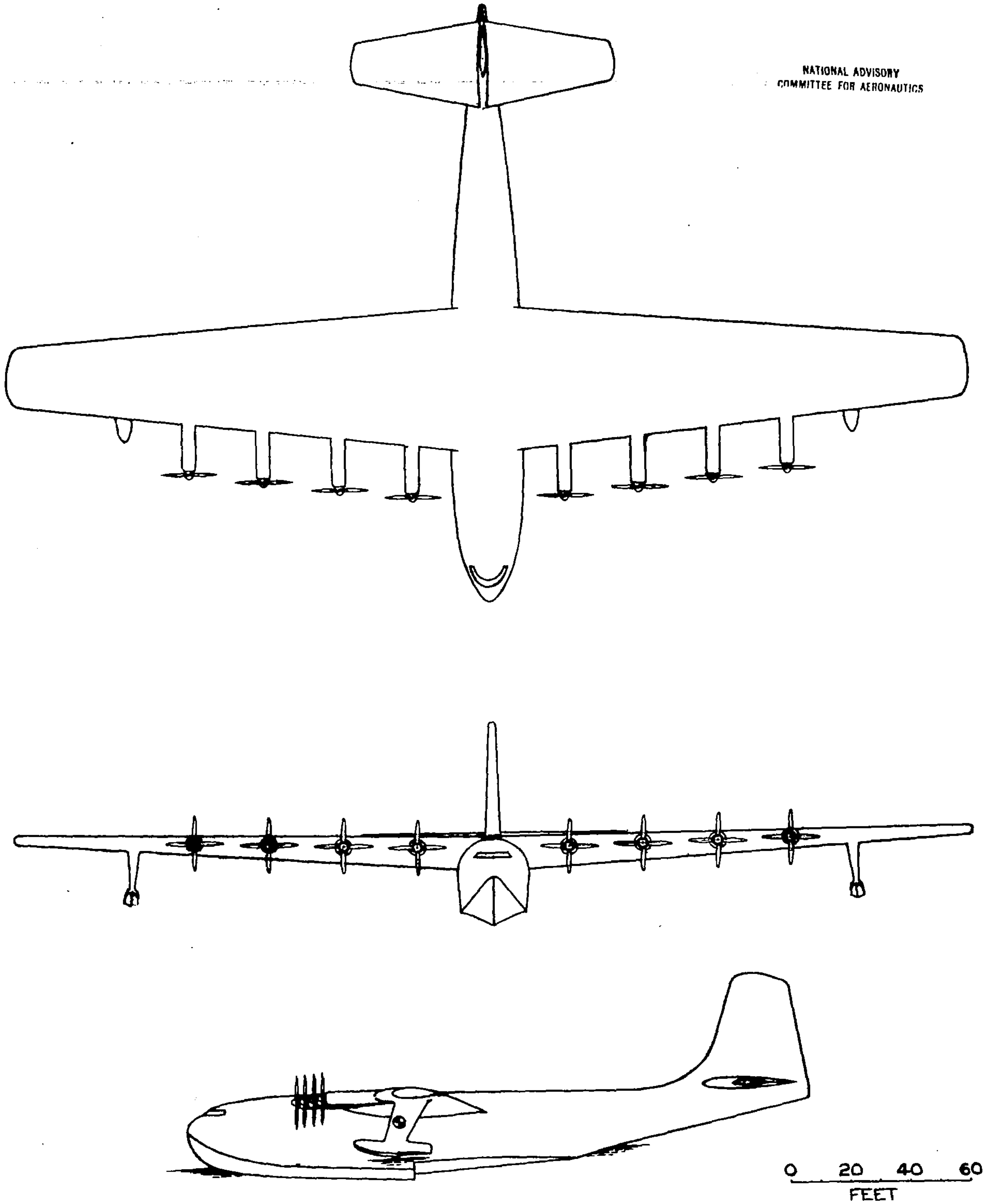

Figure 8.- Three-view drawing of Albatross. Gross weight, 480,000 pounds.

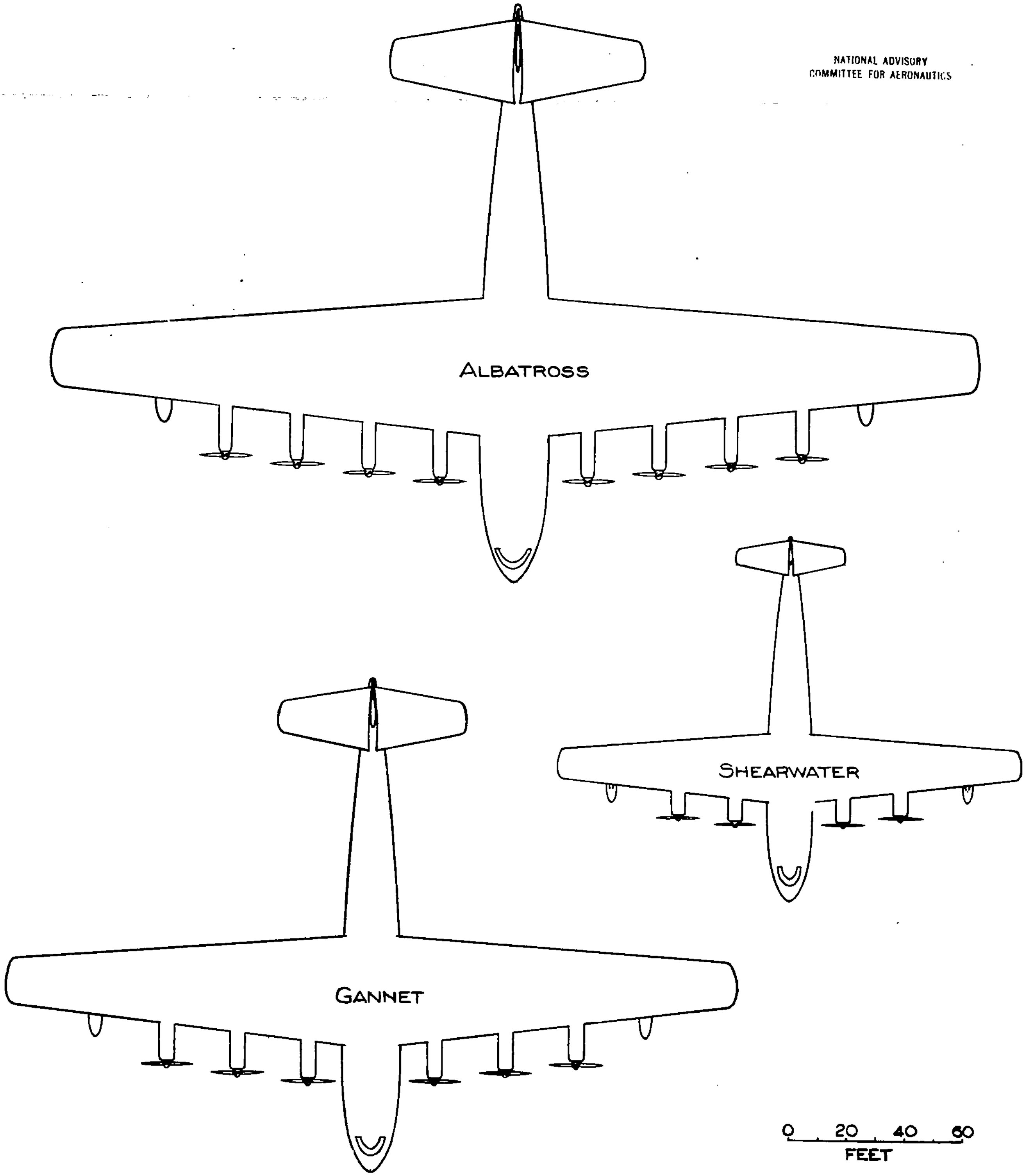

Figure 9.- Plan views of Shearwater, Gannet, and Albatross to same scale.

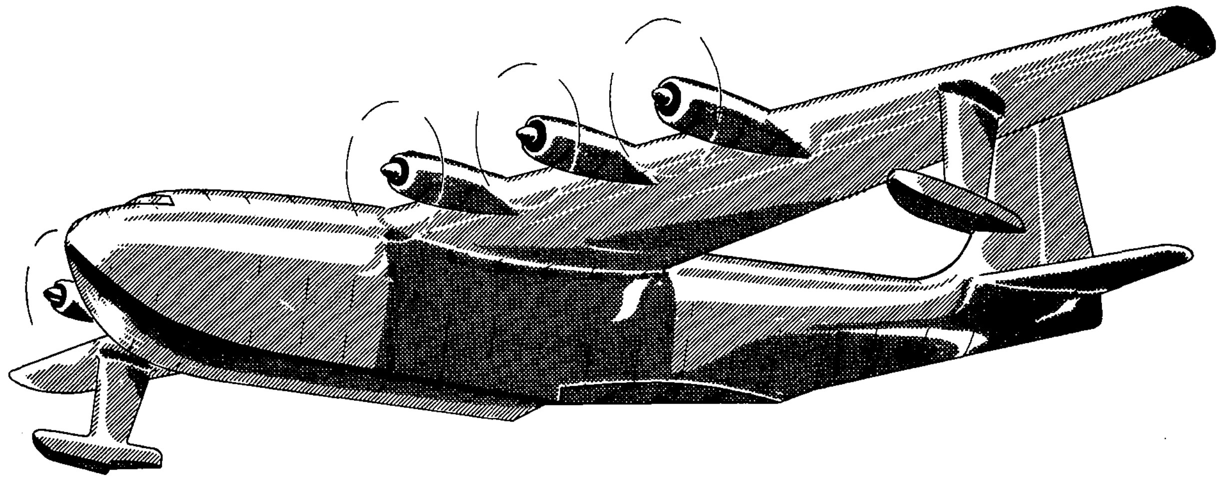

Figure 10.- Perspective drawing of Gannet. Gross weight, 300,000 pounds.

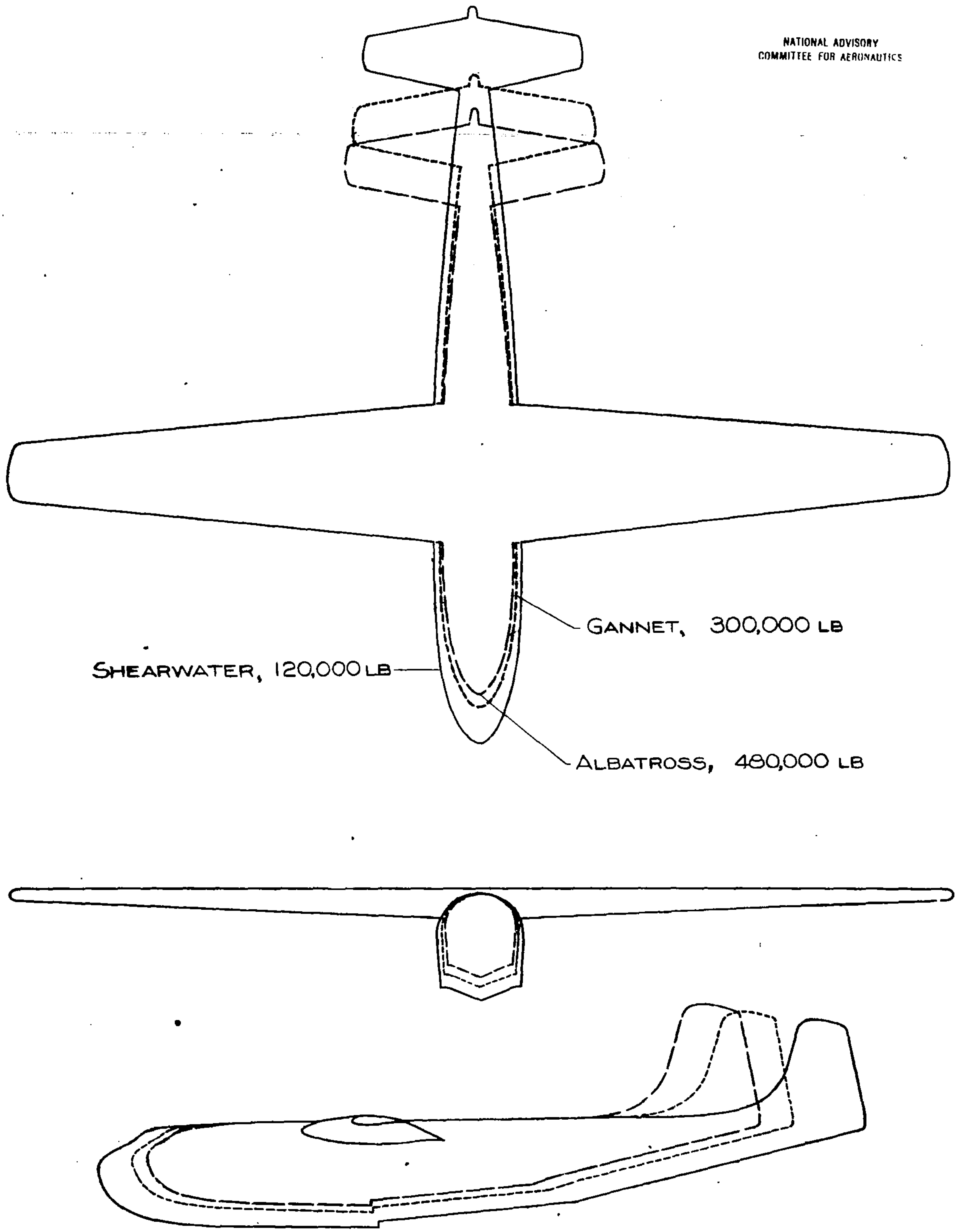

Figure 11.- Effect of gross weight on size of hull relative to wing with constant wing loading and hull load coefficient.

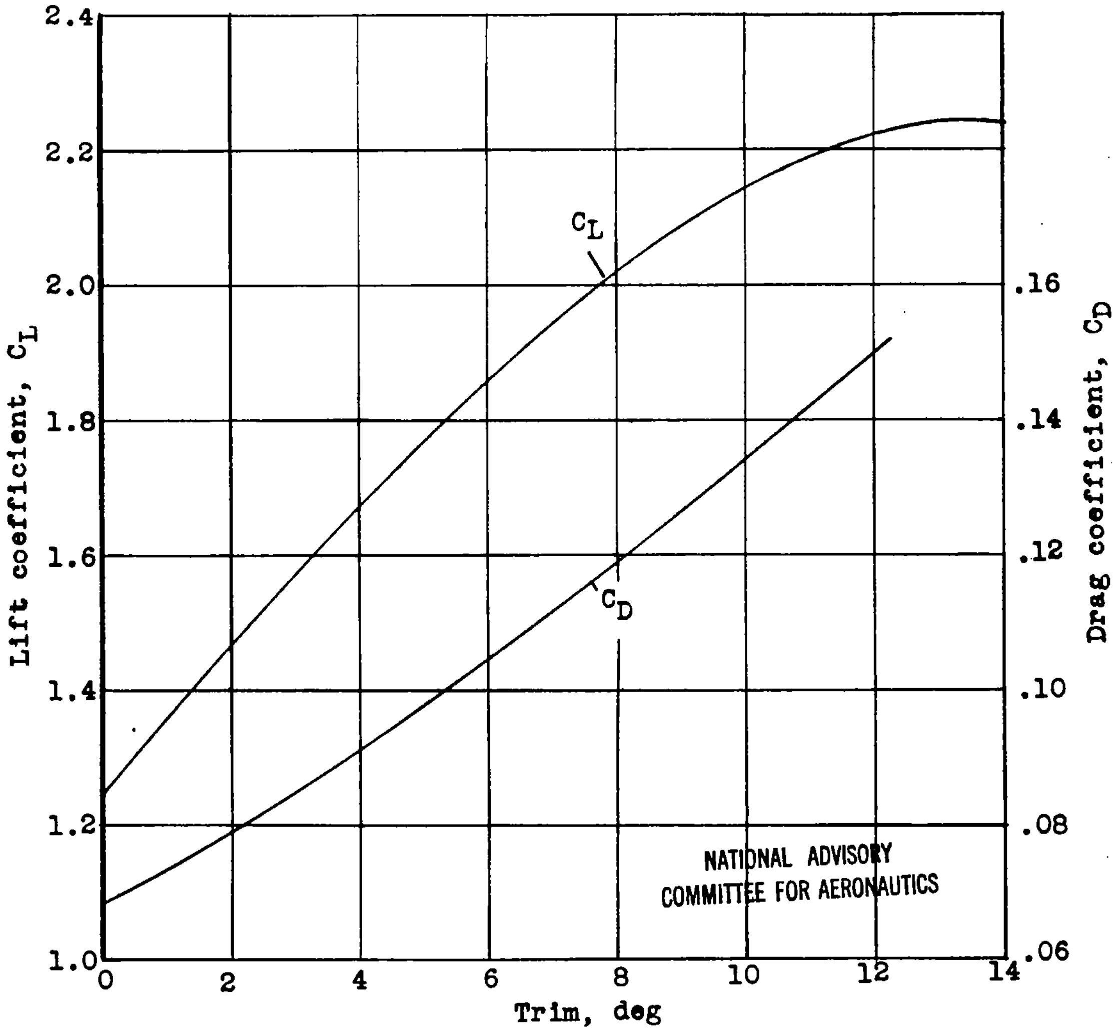

Figure 12.- Assumed lift and drag coefficients for take-off calculations. Angle of wing setting with respect to trim base line, 4°.

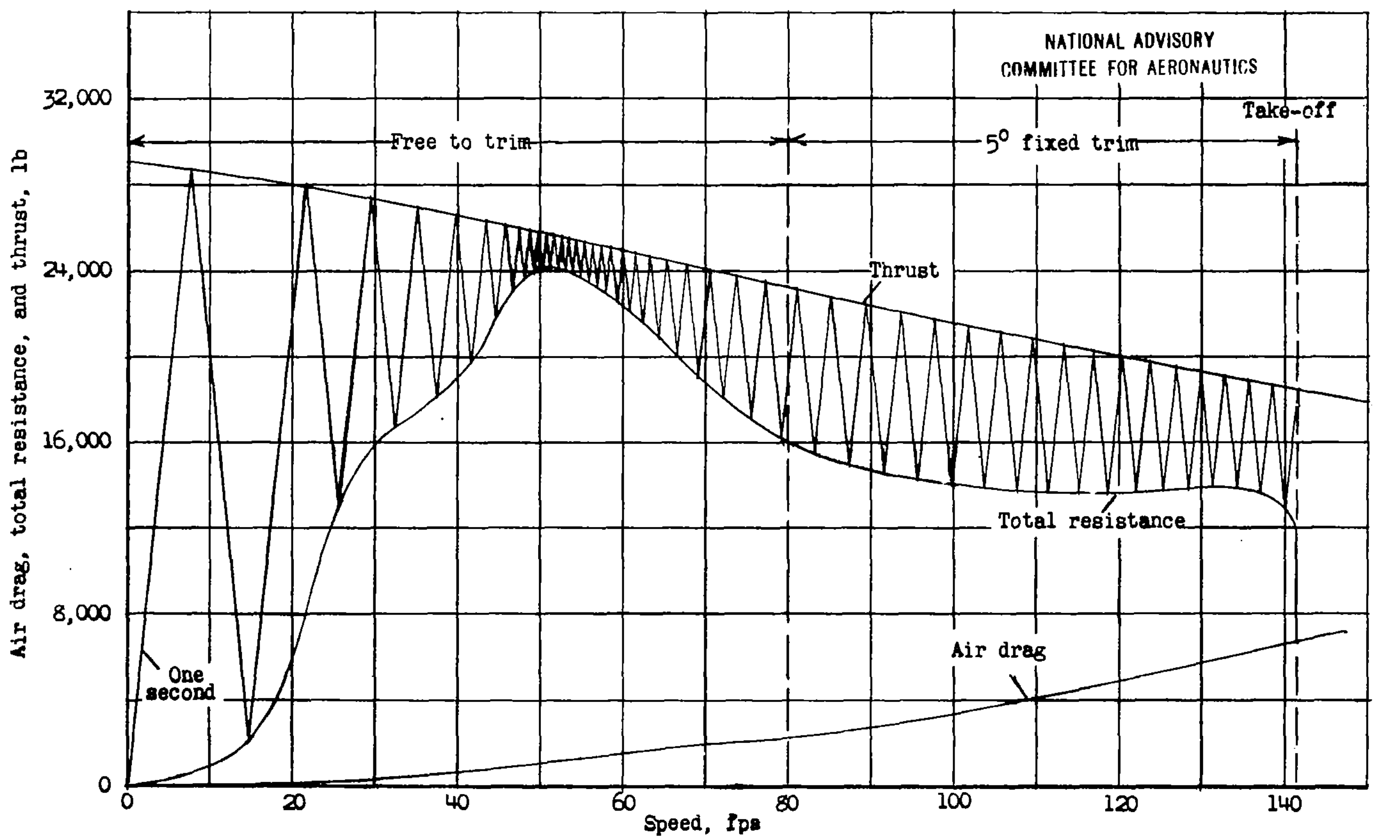

Figure 13.- Take-off performance of Shearwater. Gross weight, 120,000 pounds; take-off time, 89 seconds; take-off distance, 6820 feet.

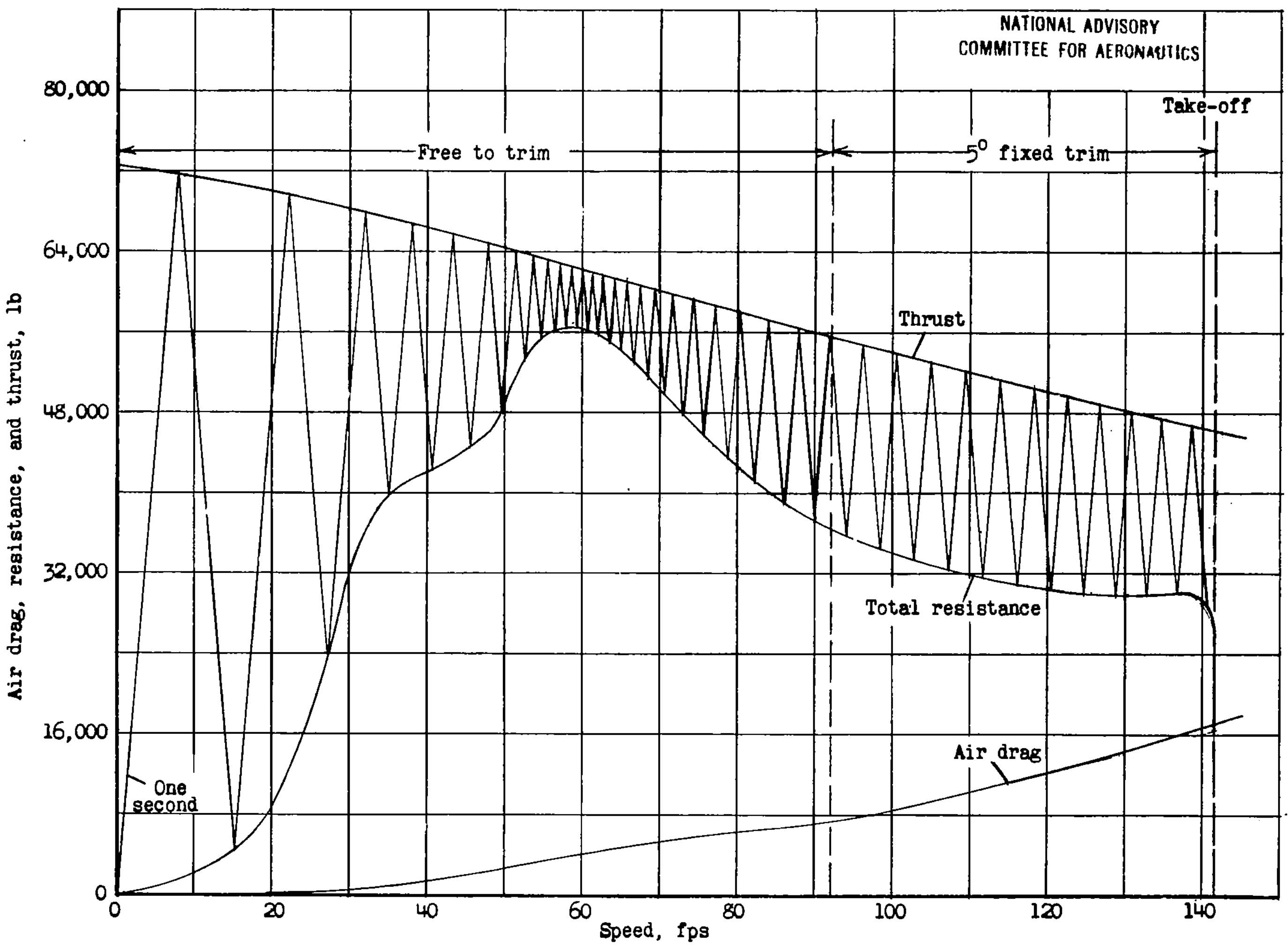

Figure 14.- Take-off performance of Gannet. Gross weight, 300,000 pounds; take-off time, 72 seconds; take-off distance, 5770 feet.

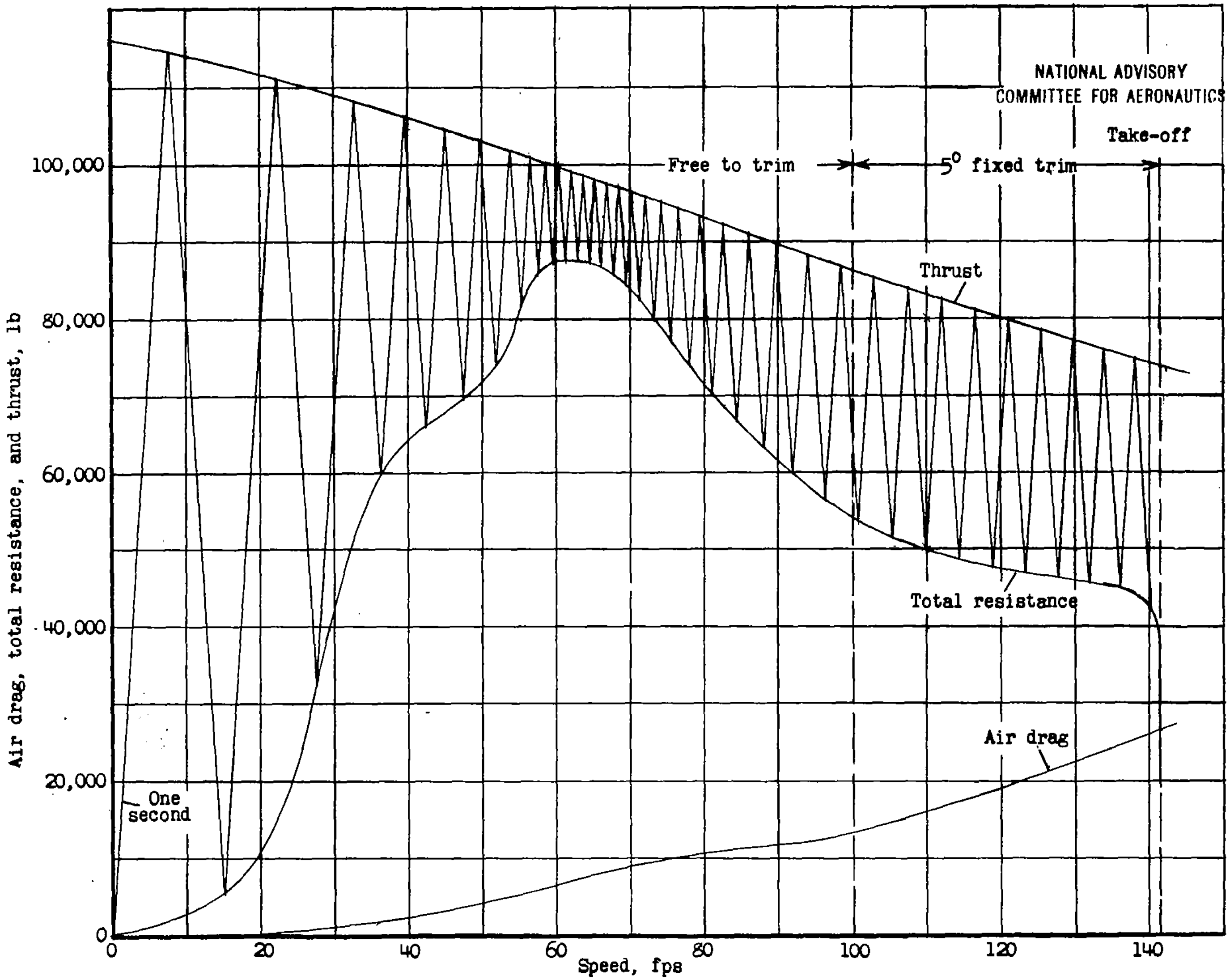

Figure 15.- Take-off performance of Albatross. Gross weight, 480,000 pounds; take-off time, 68 seconds; take-off distance, 5540 feet.

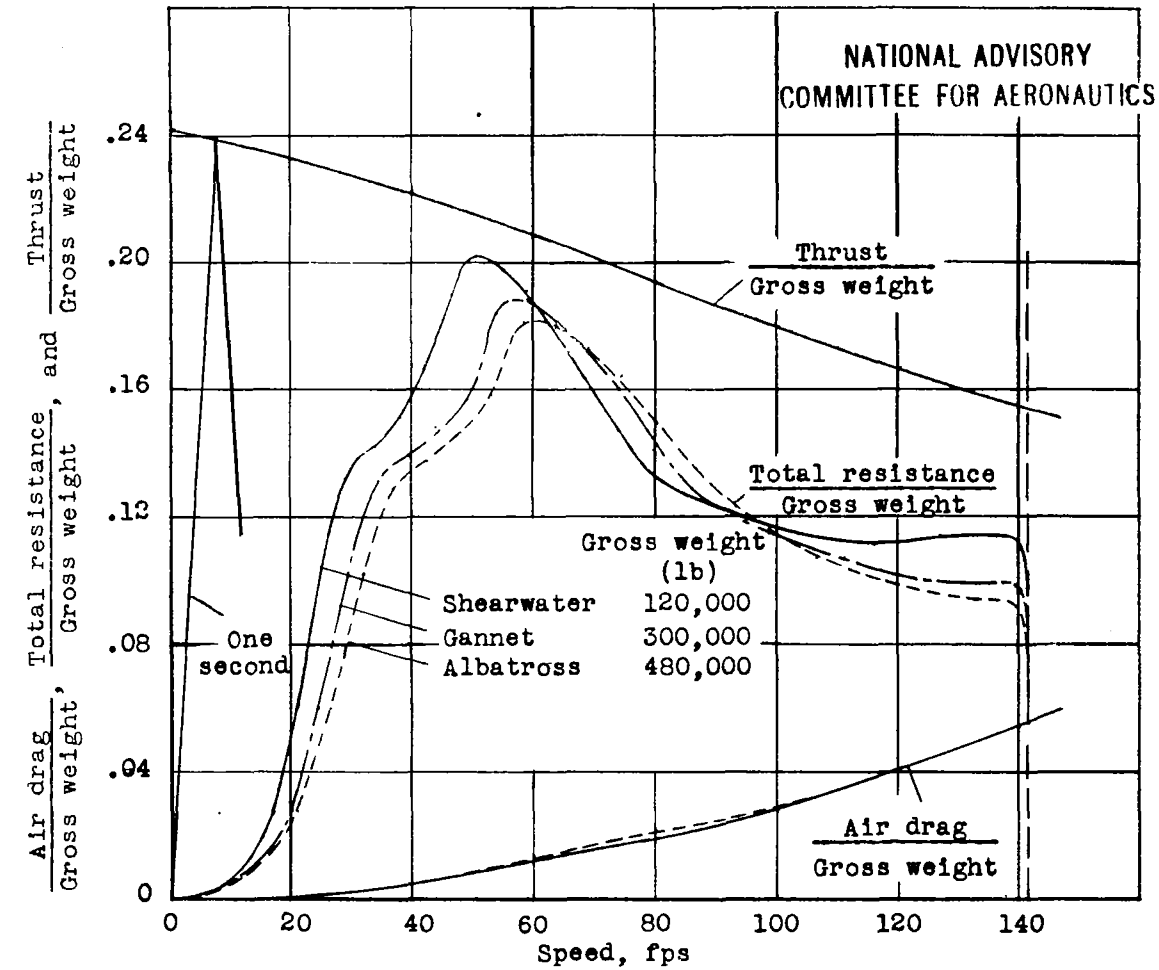

Figure 16.- Comparison of air drag, total resistance, and thrust divided by gross weight for the various sizes of airplane.